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ARTICLE

Wearable exoskeleton control modes selected during overground walking affect muscle synergies in adults with a chronic incomplete spinal cord injury

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Abstract

Study design Case series.

Background Changes in the number of muscle synergies (MSs) and in the weighting of muscles composing each MS are typically altered following an incomplete spinal cord injury (iSCI). Wearable robotic exoskeletons (WRE) represent a promising rehabilitation option, though the effects of various WRE control modes on MSs still remain unknown.

Objective This case series characterizes how WRE control modes affect the number of MSs and the weighting of muscles composing each MS in individuals with iSCI.

Setting Pathokinesioly laboratory of a rehabilitation research center.

Methods Three participants with a chronic iSCI walked at a self-selected comfortable speed without and with a WRE set in two trajectory-controlled (Total Assistance, TOT; Assistance-as-Needed, ADAPT) and three non-trajectory controlled modes (High Assistance, HASSIST; High Resistance, HRESIST; NEUTRAL). Surface EMG of eight lower extremity (L/E) muscles was recorded and used to extract MSs using a nonnegative matrix factorization algorithm. Cosine similarity and weighting relative differences characterized similarities in MSs between individuals with iSCI and able-bodied controls.

Results The mode providing movement assistance within a self-selected L/E trajectory (HASSIST) best replicated MSs in able-bodied controls during overground walking. MSs extracted with the trajectory-controlled modes differed to the greatest extent from able-bodied group MSs.

Conclusions Most WRE control modes did not replicate the motor control required for typical L/E muscle coordination during stereotypical overground walking. These results highlight the need to gain a better understanding of the effects of various control modes on L/E motor control for rehabilitation professionals to incorporate research evidence when selecting WRE control mode(s) during WRE locomotor interventions.

Introduction

Overground locomotor training with Wearable robotic exoskeletons (WRE) represents an emerging and promising neurorehabilitation intervention that aligns with the basic principles of motor learning (e.g., specificity, repetition, and intensity) promoted after a neurological lesion [1]. However, it still remains difficult to pinpoint how this intervention compares with conventional locomotor training interventions in adults with an incomplete spinal cord injury (iSCI) [2–4]. Part of this difficulty relates to the fact that almost all evidence have been gathered using WRE with total lower extremity (L/E) motorized assistance and fixed trajectory guidance during treadmill walking. As a result, after having gained sufficient experience with the WRE, active voluntary participation and stride-to-stride variability,

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which are essential components in motor learning, becomes regulated and may negatively affect walking recovery [2]. In fact, such an approach may induce a habituation and sensitization phenomenon in which the spinal cord circuits adjust rapidly to repetitive activations of the same sensory pathways [5].

To overcome these obstacles, while also increasing perceived utility and acceptability among rehabilitation professionals, some WRE manufacturers offer L/E control modes providing various levels of assistance or resistance, as well as non-imposed (i.e., non-controlled) trajectory guidance. In the neurorehabilitation context, these L/E control modes allow rehabilitation professionals to personalize WRE-based rehabilitation interventions to maximize locomotion and locomotion-related abilities. However, the effects of the various control modes on L/E muscle coordination underlying locomotion remain unknown, and clinical practice remains predominantly informed by clinical reasoning and accumulated experience.

The L/E muscle coordination can be revealed by characterizing muscle synergies (MSs) using nonnegative matrix factorization (NNMF) algorithms. This analysis usually reveals a specific number of MSs (i.e., motor modules) with muscle weightings associated with gait subcycles. In adults with iSCI, spinal locomotor control is compromised to various extents and consequently alters how the central nervous system (CNS) coordinates the muscles involved during locomotion. This generally translates into fewer L/E MSs, or an altered weighting of the different muscles involved in a given MS leading to motor impairments during gait [6]. Thus, increasing the number of MSs, or replicating the weighting of muscles similar to those synergies found in able-bodied individuals during overground locomotor training with a WRE, could theoretically translate into improved walking abilities in individuals with iSCI. However, to our knowledge, no study to date has investigated to what extent various WRE control modes may modify the number of MSs and the weighting of muscles composing each MS during overground walking with a WRE in individuals with iSCI who have recovered to various extents their ability to walk.

The aim of this case series is to examine how various WRE trajectory and non-trajectory control modes affect L/E MSs (e.g., number of MSs, weightings of muscle within a given synergy) in individuals with iSCI during overground walking with a WRE. It is hypothesized that the number of MSs and weighting of muscles composing each MS during overground walking without WRE will differ when compared with able-bodied MSs (H1). Moreover, walking with a WRE set in a non-controlled trajectory mode will increase the number of MSs and modify weightings of muscles composing each MS to levels comparable to those extracted in able-bodied individuals (H2). This research represents an initial step to strengthen evidence regarding L/E muscular coordination that will inform clinical practice on the effects of different control modes when planning personalized WRE locomotor interventions.

Methods

Participants

Three participants with traumatic chronic iSCI (ASIA Impairment Scale, AIS = C or D) below the fifth cervical neurological level were recruited for this study. Participants were included if they were able to walk overground for at least 10 m without or with a walking aid (e.g., forearm crutches); were able to follow verbal, visual, and auditory commands; and met all WRE manufacturer requirements (e.g., L/E passive range of motion limitations, moderate-to severe L/E spasticity) as verified by a comprehensive physical therapy assessment. Participants were excluded if they presented history of other neurological disorders, including nontraumatic SCI or cognitive impairments. The study was conducted at the Pathokinesiology Laboratory located at the Institut universitaire sur la réadaptation en déficience physique de Montréal. All participants provided written consent to participate. The Research Ethics Committee of the Center for Interdisciplinary Research in Rehabilitation of Greater Montreal (CRIR) approved the study (CRIR-1083-0515). All applicable institutional and governmental regulations concerning the ethical use of human volunteers were followed during the course of this research.

Clinical evaluations

Injury severity was evaluated by a certified physiotherapist using the American Spinal Injury Association Impairment Scale (AIS) to categorized participant's neurological injury level and completeness. The L/E muscle strength was assessed and graded according to the Lower Extremity Motor Score (LEMS) of the International Standards for Neurological Classification of SCI. The 10 m walking test was completed at self-selected natural velocity to evaluate walking speed and confirm the participant's ability to walk the test distance.

Robotic exoskeleton

The Ekso GT^{TM} WRE (EKSO Bionics, CA, USA) provides robotic control during overground walking. Specifically during the swing phase, the control modes offered by the Ekso GT^{TM} can be grouped into trajectory control, including total assistance (TOT) and assistance-as-needed

(ADAPT) modes, as well as non-trajectory control, including high assistance (HASSIST), high resistance (HRESIST), and NEUTRAL modes (Fig. 1). During stance, knee flexion beyond 45 degrees was blocked by the WRE to prevent full knee collapse and falling.

Intervention

Participants completed four 45–60 min training sessions over a 2-week period. During these sessions, under direct supervision of a certified physiotherapist, participants learned to safely walk with the WRE at a self-selected comfortable speed using forearm crutches and with the WRE set in the five WRE control modes along a 50 m level tiled corridor.

Laboratory assessment

Walking conditions

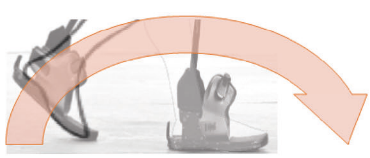
Participants walked without the WRE at a self-selected natural speed (NAT) on a leveled tiled corridor over a 10 m distance. Thereafter, participants walked with the WRE at a self-selected comfortable speed with all WRE control modes tested in a random order (i.e., participant 1: HASSIST-ADAPT-NEUTRAL-HRESIST-TOT; participant 2: NEUTRAL-ADAPT-HRESIST-TOT-HASSIST; participant 3: HRESIST-HASSIST-ADAPT-NEUTRAL-TOT). Immediately after testing each control mode, the participant's rate of perceived exertion (RPE) was collected using a modified 0–10 Borg Scale. Between modes, participants performed lateral weight shift transfers while standing for 1 min to minimize any potential carryover effects of the previously tested WRE mode (i.e., wash out).

Surface electromyography

Using a Delsys Trigno wireless EMG system (Delsys Inc., Boston, MA, USA), the EMG activity was recorded from eight L/E muscles bilaterally: gluteus medius (GM), rectus femoris (RF), vastus medialis (VM), semitendinosus (ST), biceps femoris (BF), tibialis anterior (TA), medial gastrocnemius (MG), and soleus (SO). After proper skin preparation, all wireless hybrid sensors were positioned in accordance with recommendations of the Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles (SENIAM) (www.seniam.org) to enable surface EMG (1926 Hz) and 3D acceleration data (148 Hz) recording.

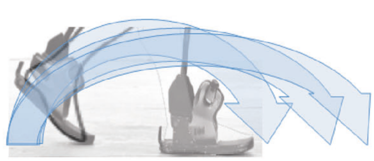
Raw EMG data were filtered (Butterworth bandpass 20–400 Hz, 4th order no lag) and processed with a continuous Root Mean Square (RMS) using a centered 250 msec moving window. Each gait cycle was delimited between consecutive foot contacts, which were determined from integrated acceleration peaks from the SO sensors using a Teager–Kaiser Energy Operator (TKEO), and then visually inspected and manually adjusted if needed. All gait cycles were time normalized to 100% with 1% increments from which the stance (0–59%) and swing (60–100%) phases were depicted. For each walking condition, the best three consecutive cycles,

1. **Trajectory controlled:** The wearable exoskeleton (WRE) automatically initiates steps when the participant reaches both predetermined lateral and forward body shift thresholds. Once the step is initiated, the exoskeleton swings and controls the hip and knee kinematics for the foot to follow a specific pathway.



1.a. TOT	Provides total motorized assistance continuously to move the hip and knee joints according to a predefined planned hip and knee kinematics configured to drive foot position during the swing phase.
1.b. ADAPT	Provides adaptable motorized assistance to continuously adjust hip and knee joint movements to comply with a predefined planned hip and knee kinematics configured to drive foot position during swing phase.

2. **Non-trajectory controlled (i.e., 'free legs'):** The participant initiates swing and control freely his L/E kinematics (amplitude, velocity, and acceleration) within the sagittal plane (i.e., no predefined trajectory) during the swing phase of each step.



2.a. NEUTRAL	Provides no assistance and no resistance at the hip and knee joints during swing phase. Only gravity compensation assistance is provided.
2.b. HASSIST	Provides high assistance to facilitate hip flexion and knee extension during swing phase.
2.c. HRESIST	Provides high resistance to augment hip flexor and knee extensor muscular efforts during swing phase.

Fig. 1 Description of the different exoskeleton control modes investigated during the swing phase when walking with the wearable robotic exoskeleton.

based on the lowest mean coefficient of variation computed for all EMG envelopes over each temporal data point embedded within each time normalized cycles, were automatically selected using a custom-made Labview software before being averaged and amplitude-normalized (i.e., the RMS from each muscle was divided by its own maximum peak value prior to initiating the MSs analysis).

Muscle synergies

An experimental EMG data matrix was calculated for each participant, consisting of the mean of three consecutive gait cycles of each recorded muscle, prior to being submitted to a NNMF algorithm. The number of MSs was determined by the least number of synergies that could explain the variance accounted for (VAF) in each muscle (VAF_m), with VAF_m >0.9 (90%) and the product of all VAF_m (global VAF, VAF_g) >0.8 (80%). MSs were grouped based on the Cosine Similarity (CS) of the weight matrices (W) [7, 8]. To analyze the resemblance between the obtained MSs of each walking condition against reference MSs computed among an able-bodied control, CS was calculated between each participant MSs (Wr) against those obtained from a reference participant [9]. The reference MSs were extracted from an able-bodied participant (i.e., control) who was assessed during overground walking without the exoskeleton using the same experimental protocol (i.e., equipment, recorded muscles, and experimental conditions) [10]. For this analysis, the inner product of the obtained MSs on each walking trial was calculated and the cosine angle between those synergies and the reference MSs was measured.

According to the reference able-bodied control, the muscles composing each MS were established as: Synergy #1, GM, VM and to a lesser extent, RF; Synergy #2, SO and MG; Synergy #3, TA and RF; Synergy #4, ST and BF. The CS values closer to one indicated greater similarities in the directions of the two compared vectors. When the CS between Wr and Wt was >0.868 and statistically significant ($p < 0.05$) [11], MSs were considered similar. Whenever two distinct MSs in the same walking trial were classified into the same group, these two synergies were considered to have merged together. The synergy with the lowest correlation of the two was deemed to be merged to the synergy presenting the highest correlation value. Synergies not corresponding to any of the reference MSs extracted in able-bodied control were defined as "undefined".

To further visualize how each recorded muscle weighting contributing to a specific synergy was similar to those found in able-bodied reference, the weighting differences (Wd = Wt−Wr) for each muscle and walking trial, were calculated for each participant (Fig. 2). In order to calculate Wd, muscles belonging to a specific synergy were weighted by multiplying each muscle in the weight matrix by its maximum peak value found to obtained normalized values to one within each synergy and allow weighting matrices subtractions.

Statistical analyses and interpretation

Differences in MS weightings (Wd) equal to 0 represented perfect matches while values closer to 1 indicated larger divergences in MS weighting, with values ranging between 0 and 0.3 [12] considered to closely reproduce MSs weightings from the able-bodied control. The RPE values were calculated and interpreted according to the American College of Sports Medicine (ACSM) guidelines for exercise testing and prescription to determine the exercise intensity achieved while walking with the WRE [13, 14]. According to these guidelines, an RPE of 1–2 corresponds to very light to light intensity, 3–4 corresponds to a moderate intensity, 5–6 corresponds to a high intensity, and 7–10 corresponds to a very high intensity.

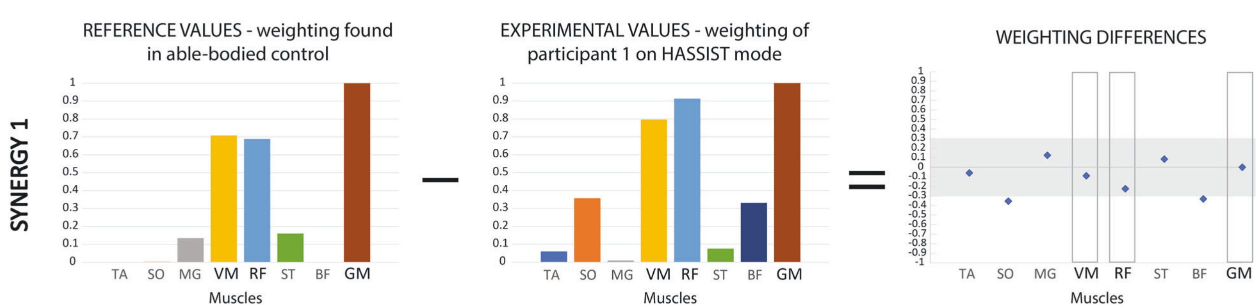


Fig. 2 Example of the procedure to calculate muscle weighting differences. Normal weighting matrix obtained on healthy individuals were subtracted to the obtained experimental tasks. The vertical gray boxes represent main muscles composing a specific muscle synergy while horizontal gray boxes represent the threshold range, i.e., ≤0.3 for a value to be considered similar or close-to normal compared with a healthy reference. In this example, notice that synergy #1, mainly composed by VM, RF, and GM muscles, presented almost perfect similarities with the HASSIST mode for participant 1 (color figure online).

Results

Participants and walking speed

All demographic, clinical characteristics, and walking speed during each experimental trial are summarized in Table 1. Overall, compared with overground walking without WRE (i.e., NAT), walking with the WRE reduced speed between −63.2 and −78.2% for participant 2 and between −55.6 and −66.7% for participant 3, across all WRE control modes. Participant 1 predominantly walked faster than NAT by up to 42.1%.

Number of muscle synergies

Three to four MSs were found across walking conditions (VAF > 0.8 for all conditions). Synergy #4 was absent in all participants with iSCI during NAT condition but present during all WRE control modes, except for participant 1 who had three synergies in TOT mode. Merging of MSs were observed and mostly found between synergies #1 and #4. Interestingly, only HASSIST mode consistently had all four synergies in able-bodied reference with relatively high CS values and no merged synergies. Undefined MSs were also found in most WRE control modes, except for HASSIST, which presented only one undefined synergy across all participants (Table 2).

Table 1 Demographic and clinical information of participants.

Participants	1		2		3	
Demographic characteristics						
Gender	M		F		M	
Age (years)	42		51		60	
Height (m)	1.80		1.62		1.60	
Weight (Kg)	65.7		52.1		56.6	
Clinical Information						
Time since injury (years)	18		1.1		40.7	
Neurological level of injury	T6-T7		C5		T4	
American Spinal Injury Association Impairment Scale (AIS)	D (Trauma)		D (Trauma)		D (Trauma)	
Sensory level and score /224	T7 197/224		C6 132/224		T4 156/224	
Total Lower Extremity Motor Score (LEMS)	36/50		41/50		46/50	
	R	*L*	*R*	*L*	*R*	*L*
Hip flexors	4	3	5	5	3	5
Knee extensors	2	3	5	5	5	5
Ankle dorsiflexiors	4	4	4	4	5	5
Long toe extensors	4	4	4	4	3	5
Ankle plantar flexors	4	4	2	3	5	5
Walking speeds (m/s)						
Walking conditions						
Without Exoskeleton	NAT	0.19		0.87		0.54
	Control modes					
	TOT	0.18		0.19		0.21
	ADAPT	0.20		0.25		0.24
With Exoskeleton	NEUTRAL	0.27		0.28		0.23
	HASSIST	0.25		0.26		0.23
	HRESIST	0.23		0.32		0.18

R right, *L* left.

Muscles synergy weightings

Table 2 illustrates similarities between weight matrices for each synergy and for each participant compared with an able-bodied reference using CS values. MS weightings during NAT varied widely across participants, particularly between the left and right L/E. The Wd analysis showed that TOT and ADAPT modes had very different patterns from the reference muscle weightings, illustrated by the scattered data point patterns of muscle weighting relative differences across participants and across MSs presented in Fig. 3.

Although some MSs weighting relative differences approached the 0.3 value threshold across the WRE control modes, only HASSIST consistently presented a clustering of point values around the 30% threshold on all participants and on both L/E. This confirms strong similarities between the HASSIST mode and the typical weight of muscles composing each MS found in the able-bodied reference.

Rate perception of effort (RPE)

The RPE across the different walking conditions are summarized in Fig. 4. Participants perceived effort levels ranging from light to moderate, with the greatest effort in HRESIST mode.

Discussion

The present study investigated the effects of different WRE control modes on MSs during walking in individuals with a chronic iSCI. To our knowledge, this is the first study investigating differences in MSs across a range of WRE modes. The three participants presented different degrees of sensorimotor impairment and functional disabilities resulting from their iSCI. The high variability across MSs attributes found across participants highlight the heterogeneity of muscle coordination challenges in adults with iSCI. Reduction in the number of MSs has been associated with an increased muscle co-contraction, poor muscle strength, or restricted joint range of motion because the CNS cannot independently and efficiently access and activate MSs during walking [6, 15, 16]. Clinically, these MSs deficits typically translate into abnormal motor outputs, decreased walking speeds, and increased gait asymmetry [6]. Thus, the reductions in the

Table 2 Cosine similarities for all participants and walking trials. Notice that HASSIST mode presented four synergies with relatively high cosine similarities values, no merged and only one undefined synergy (values in italic).

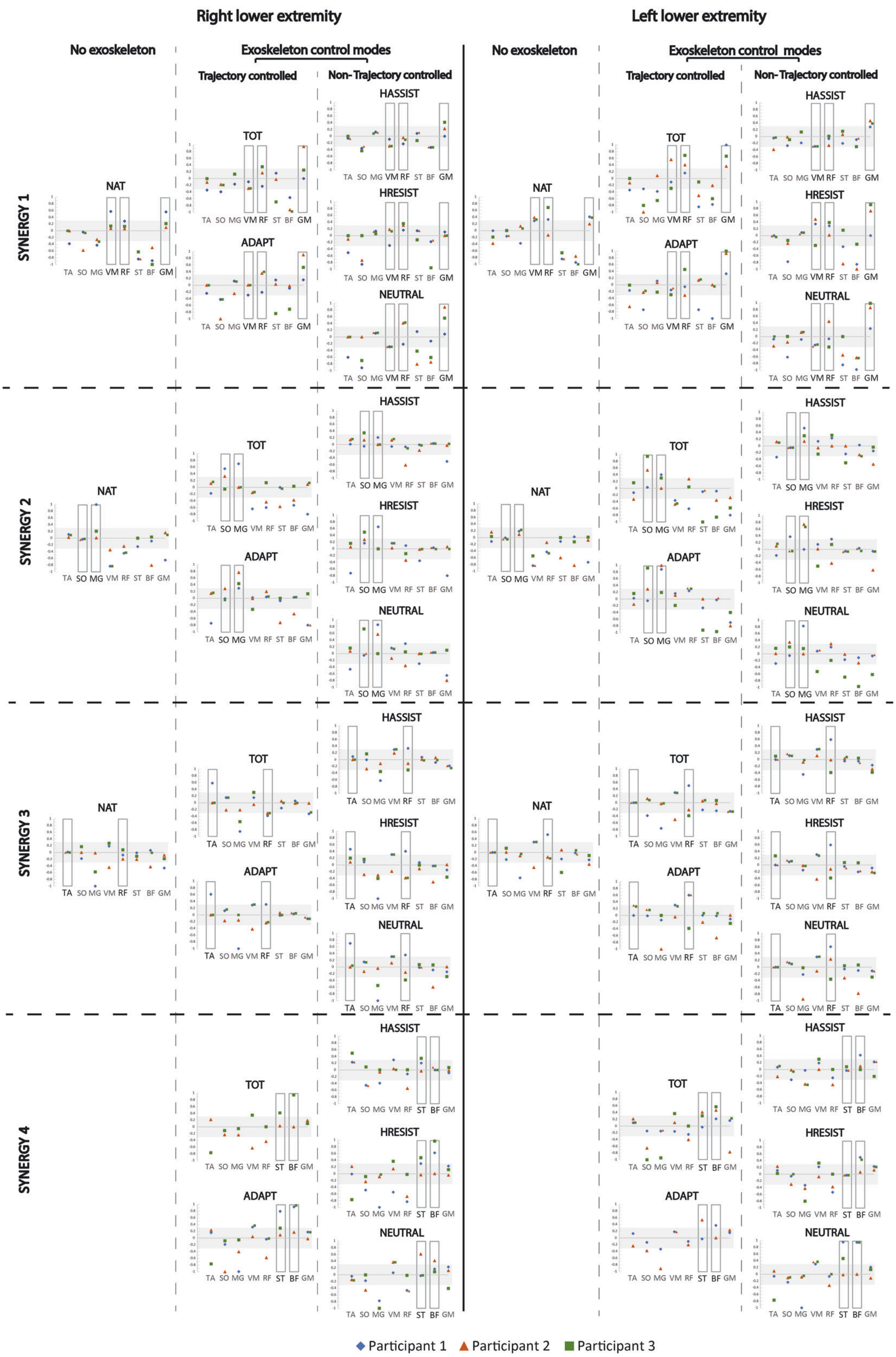
	Walking conditions											
	Without exoskeleton		With exoskeleton									
			Control modes									
Participants	NAT		TOT		ADAPT		NEUTRAL		HASSIST		HRESIST	
	R	*L*	*R*	*L*	*R*	*L*	*R*	*L*	*R*	*L*	*R*	*L*
Synergy 1												
P1	0.71	0.68	0.88	0.78	0.91	~#4	0.78	~#4	*0.94*	*0.92*	0.78	~#4
P2	0.76	0.81	0.73	~#3	0.63	~#3	0.75	~#4	*0.85*	*0.81*	0.8	0.69
P3	0.83	0.76	~#4	~#4	~#4	0.56	0.63	0.64	*0.83*	*0.82*	0.76	0.63
Synergy 2												
P1	0.69	0.81	0.81		0.79	0.8	0.74	0.83	*0.75*	*0.83*	0.74	0.92
P2	0.85	0.75	0.82	0.78	0.81	~#4	0.8	0.92	*0.9*	*0.91*	0.94	0.85
P3	0.82	0.86	0.97	0.74	0.91	0.75	0.94	~#4	*0.84*	*0.81*	0.92	0.83
Synergy 3												
P1	0.87	0.67	~#2	0.67	~#1	0.82	~#4	0.79	*0.78*	*0.77*	~#1	0.8
P2	0.91	0.92	0.96	0.92	0.94	0.87	0.9	0.91	*0.95*	*0.95*	0.88	0.93
P3	0.84	0.86	0.85	0.92	0.94	0.87	0.84	0.91	*0.89*	*0.88*	0.83	0.87
Synergy 4												
P1			0.94	0.82	0.91	0.8	0.81	0.8	*0.9*	*0.87*	0.8	0.68
P2			0.69	0.86	0.68	0.7	0.87	0.87	*0.92*	*0.93*	0.89	0.88
P3			0.86	0.84	0.88	0.85	0.78	0.71	*0.87*	*0.78*	0.77	0.84
UD Synergy												
P1			X		X	X	X	X			X	X
P2				X		XX		X				X
P3			X	X	X	X		X		*X*	X	X

~#X = synergy merged with synergy number X.

number of MSs and altered muscle weighting within each MS were expected and fully support the first hypothesis (H1) that the number and weighting of muscles composing each MS during overground walking without WRE will be different than able-bodied MSs.

Synergy #4 emerged while walking with the WRE in all control modes, with varying muscle weightings across participants and L/E sides. Although more MSs reflects improved motor function [17], the results prove otherwise since the more synergies during walking with the WRE did not necessarily match the typical weighting of muscles composing each MS. Indeed, most MSs weightings across control modes were different from those found in able-bodied controls during overground self-selected natural speeds. These findings indicate that, even during TOT and ADAPT control modes during which the L/E trajectory remains totally guided through typical, strict, and repetitive kinematics patterns [1], adaptations to these modes did not lead to a typical muscle activation pattern in adults with a chronic iSCI. This is of great relevance because TOT or ADAPT control modes, which are the most commonly used modes in the literature to explore superiority effects of robotic exoskeleton over other conventional locomotor training interventions in adults with iSCI [2], might not reinforce an adequate neural locomotor pattern for locomotion.

A key finding of this study, which partially supports the second hypothesis (H2), is that only HASSIST mode consistently replicated the number of MSs and weight of muscles composing each MS in the reference able-bodied individual. These findings were observed in both L/Es among all participants and in all main and secondary muscles composing each MS. This is demonstrated by the relative difference values below the 30% threshold set to establish similarities with able-bodied controls. Such effect of the HASSIST mode may result from an increased step variability triggered by the free/non-imposed L/E trajectory while allowing voluntary motor control, providing the assistance that may reduce the need of compensation or activation from other muscles that normally would not participate in a typical synergy. These elements might facilitate the recruitment of MSs similar to those found during overground walking in healthy individuals. Concerning NEUTRAL and HRESIST modes, this MSs



weighting “normalization” was not achieved since the lack of assistance and increased limb motion resistance, alongside potential under-optimal compensations for the dynamics of the WRE, might have increased the probability of recruiting additional secondary/compensatory muscles to adapt to the new demands, which translated

◀ **Fig. 3 Right and left muscle synergies weightings relative differences for all experimental trials and for each participant.** The vertical gray boxes highlight the muscles defining a specific muscle synergy (i.e., the muscles that contribute the most on a synergy in heathy individuals). The light gray horizontal band represents the limits of 30% within which the synergies are found to be similar to those found in healthy individuals. Notice that for all synergies, the HASSIST mode consistently tended to bring the muscle weightings closer to 30% in all participants. TA tibialis anterior, SO soleus, MG medial gastrocnemius, VM vastus medialis, RF rectus femoris, ST semitendinosus, BF biceps femoris, GM gluteus medius (color figure online).

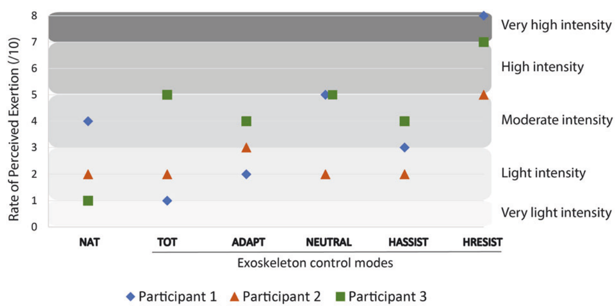


Fig. 4 Ratings of perceived effort during all walking trials for each participant. Areas highlighted in various shades of gray represent different exercise intensities (i.e., very light, light, moderate, vigorous, near maximum intensity, maximal, and sub-maximal effort) according to the ACSM's guidelines (color figure online).

into different muscle weightings found in able-bodied individuals.

This study provided new evidence that has the potential to impact clinical practice. First, although not all WRE control modes induced motor control adaptations closer to the able-bodied reference, the results showed that typical MS characteristics found in abled-bodied individuals during overground walking without a WRE could be reproduced when individuals with iSCI ambulate with WRE. These aspects might have important implications when selecting WRE control modes before engaging on locomotor training programs using this technology. Second, when exploring the level of effort required to walk during all WRE non-trajectory-controlled modes, the HASSIST mode required a light to moderate effort from all participants to accomplish the walking task. Thus, this control mode could be used to facilitate the swing phase during prolonged periods of walking (i.e., massed practice) and, ultimately, induce beneficial neural plasticity and potentiate locomotor recovery [18].

This study had several limitations. First, the small sample of adults with a chronic iSCI does not allow generalization of the results. In fact, other individuals may benefit from other WRE control modes. Second, since no kinematic analysis was completed in the present study, it remains difficult to determine to what extent WRE movement strategies were similar to those established for overground walking. Lastly, the actual absolute level of assistance or resistance provided remains unknown and is not provided by the WRE manufacturer.

Conclusion

Walking with a WRE in control modes allowing step variability (i.e., self-selected trajectory), and assisting L/E swing phase (i.e., HASSIST), best replicated MSs observed in able-bodied individuals during overground walking, while requiring light to moderate effort. This control mode may allow adults with iSCI to engage in a high-repetition task-specific walking program (i.e., activity-based therapy) needed to induce neuroplastic adaptations and potentiate walking ability. Additional studies with more robust experimental designs and larger sample sizes are needed to strengthen evidence and further support clinical decision-making processes when aiming to improve L/E motor control during walking. Nonetheless, the results of the present study are a first step towards a better understanding of the effects of various control modes on L/E muscular coordination, which can be evaluated through MSs when individuals with iSCI walk with a WRE.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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